National Aeronautics and
Space Administration

Educational Product	
Educators & Students	Grades 9-12

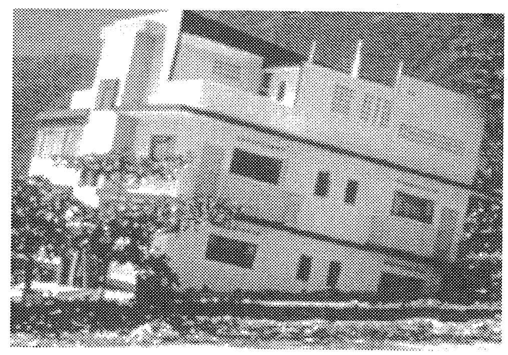
EB-2002-06-53-MSFC

Educational Brief

Using Space for a Better Foundation on Earth
Mechanics of Granular Materials

For the Educator

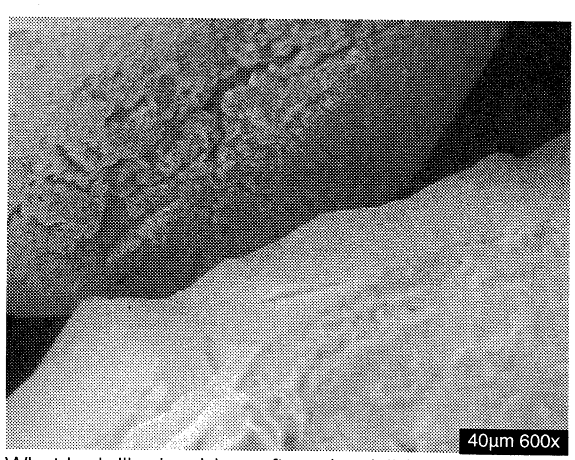
Anyone who has ripped open a vacuum-packed pouch of coffee has experienced a fundamental aspect of mechanics of granular materials: a single shift in conditions can drastically change the properties of a bulk material. While the coffee pack is sealed under vacuum, outside air presses the grains against one another, locking each in place and creating a stiff "brick." Once pressure is released, the grain assembly becomes very weak and soft, and moves about freely, almost like a liquid.


A partially sunken house illustrates the challenge of understanding how grains of soil interact with each other and under what conditions they will support structures. (National Geophysical Data Center)

The principal strength of granular materials—whether they are coffee, soil beneath a house, or sand under a rover's wheels on Mars—is interparticle friction and geometric interlocking between particles. Billions of grains contribute to the total strength of the material. This is relevant to many fields, not the least being earthquakes, which can loosen compacted soil and compact loosened soil.

Studying Soil Strength in Space

Detailed understanding of this phenomenon is needed to improve techniques for evaluating building sites here on Earth and, eventually, on the Moon and Mars, and to improve industrial processes that handle powdered materials. Research can only go so far on Earth because gravity-induced stresses complicate the analysis and change loads too quickly for detailed study. Going to orbit, though, opens new possibilities. The Mechanics of Granular Materials (MGM) experiments use the microgravity of orbit to test sand columns under conditions that cannot be obtained in experiments on Earth. This new knowledge will be applied to improving foundations for buildings, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries. MGM has flown on two Space Shuttle missions and is scheduled for a third, STS-107 in 2002.



What look like boulders after a landslide are just sand grains seen under an electron microscope. Each tiny facet can stick to another grain and cause internal friction. (IITRI)

Because the experiment apparatus used in MGM includes a complex hydraulic system, this educational brief offers a simpler laboratory demonstration, the displacement shear test, of soil mechanics. Although this displacement shear test and MGM use different

approaches and apparatus, both ultimately depend on the interlocking between individual grains of sand. High school teachers may want to have their students first conduct the sand liquefaction activity in the Mechanics of Granular Materials brief (EB-2002-06-52-MSFC). Although designed for middle school students, this brief provides a good, entertaining introduction to sand liquefaction for students of all ages.

Education Standards

Education standards for grades 9–12 met by this classroom activity are listed below. For brevity, standards which are not met are not included in this list.

Standards for Technological Literacy (International Technology Education Association)

The Nature of Technology
- The characteristics and scope of technology.
- The core concepts of technology.
- The relationships among technologies and the connections between technology and other fields of study.

Technology and Society
- The effects of technology on the environment.

Design
- The attributes of design.
- Engineering design.
- The role of troubleshooting, research and development, invention and innovation, and experimentation in problem solving.

Abilities for a Technological World
- Abilities to apply the design process.
- Abilities to use and maintain technological products and systems.
- Abilities to assess the impact of products and systems.

Principles and Standards for School Mathematics (National Council of Teachers of Mathematics)

Algebra Standard
- Understand patterns, relations, and functions; and
- Represent and analyze mathematical situations and structures using algebraic symbols.

Measurement Standard
- Understand measurable attributes of objects and the units, systems, and processes of measurement; and
- Apply appropriate techniques, tools, and formulas to determine measurements.

Data Analysis and Probability Standard
- Formulate questions that can be addressed with data and collect, organize, and display relevant data to answer them;
- Select and use appropriate statistical methods to analyze data; and
- Develop and evaluate inferences and predictions that are based on data.

Problem-Solving Standard for Grades 9–12
- Build new mathematical knowledge through problem solving;
- Solve problems that arise in mathematics and in other contexts;
- Apply and adapt a variety of appropriate strategies to solve problems; and
- Monitor and reflect on the process of mathematical problem solving.

Communication Standard
- Organize and consolidate their mathematical thinking through communication;
- Communicate their mathematical thinking coherently and clearly to peers, teachers, and others;
- Analyze and evaluate the mathematical thinking and strategies of others; and
- Use the language of mathematics to express mathematical ideas precisely.

Connections Standard for Grades 9–12
- Recognize and apply mathematics in contexts outside of mathematics.

Representation Standard
- Create and use representations to organize, record, and communicate mathematical ideas;
- Select, apply, and translate among mathematical representations to solve problems; and
- Use representations to model and interpret physical, social, and mathematical phenomena.

National Science Education Standards (National Academy of Sciences)

Unifying Concepts and Processes
- Systems, order, and organization
- Evidence, models, and explanation
- Change, constancy, measurement

Science as Inquiry
- Abilities necessary to do scientific inquiry
- Understandings about scientific inquiry

Physical Science
- Structure and properties of matter
- Motions and forces
- Interactions of energy and matter

Science and Technology
- Abilities of technological design
- Understandings about science and technology

Science in Personal and Social Perspectives
- Natural and human-induced hazards
- Science and technology in local, national, and global challenges

History and Nature of Science
- Science as a human endeavor
- Nature of science

SHEAR STRENGTH OF SAND

Abstract

Soils are three-phase composite materials that consist of soil, solid particles, and voids filled with water and/or air. Based on the particle-size distribution, they are generally classified as fine-grained (clays and plastic silts) and coarse-grained soils (nonplastic silts, sand, and gravel). Soil's resistance to **external loadings** is mainly derived from **friction** between particles and **cohesion**. Friction resistance is due to particles' surface-to-surface friction, interlocking, crushing, rearrangement, and dilation (or expansion) during **shearing**. Cohesion can be due to chemical cementation between particles, **electrostatic** and **electromagnetic forces**, and soil-water reaction and equilibrium. The basic factor responsible for the strength of coarse-grained soils is friction. Cohesion can be ignored.

This educational brief focuses on measuring **shear strength** of sands (typical example of coarse-grained soils) where, for the same material, **packing density** is a main factor to be considered when one asks about the shear strength value. Figure 1 illustrates the effect of shearing on the packing density of sand. As the external load is applied, the soil's resistance is attained through shearing resistance, which causes the soil volume to increase (expand) or decrease (compress) depending on the initial packing density.

Introduction

Anyone who has ripped open a vacuum-packed pouch of coffee has experienced a fundamental aspect of mechanics of granular materials: a single shift in conditions can drastically change the properties of a bulk material. While the coffee pack is sealed under vacuum (negative pressure), the grains push against one another, locking each other in place, creating a stiff "brick-like" material. Once pressure is released, the grain assembly becomes very weak and soft, and moves about freely, almost like a liquid.

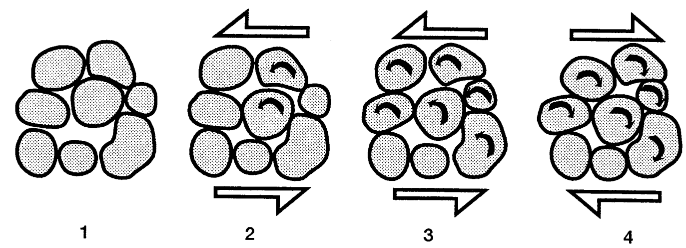


Figure 1. The packing of particles can change radically during cyclic shear; (1) a large hole is maintained by the particle interlocking; (2) a small counterclockwise strain causes the hole to collapse; (3) large shear strain causes more holes to form; (4) holes will collapse when the strain direction is reversed (*Youd, 1977*).

The principal strength of granular materials—whether they are coffee, soil beneath a house, or sand under a rover's wheels on Mars—is **interparticle friction** and **geometric interlocking** between particles. Billions of grains, ranging in size from large to microscopic, contribute to the total strength of the material. Moisture and air trapped within the soil also affect its behavior if loading occurs faster than the entrapped fluid can escape. As the pore water pressure or air pressure increases, the effective or interparticle stresses or pressures decrease, weakening and softening the soil. When the external loading equals the internal pore pressure, the soil liquefies.

This is relevant to many fields, not the least being earthquakes, which can loosen compacted soil and compact loosened soil. When this happens, buildings sink and buried struc-

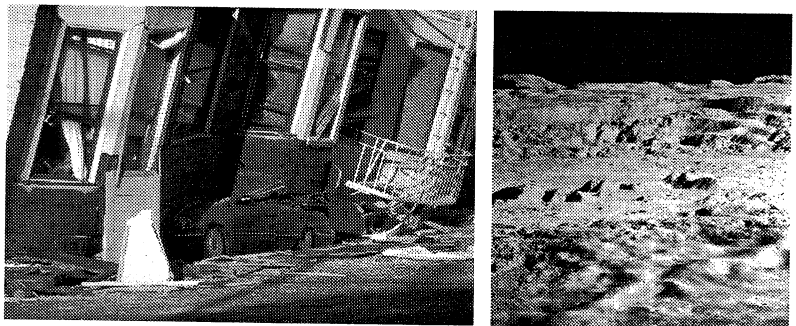


Figure 2. Partially sunken houses in San Francisco and the slumped sides of Copernicus crater on the Moon share one geologic fact: soil liquefaction. (USGS, NASA)

tures float to the surface, as happened in the San Francisco Bay area in the October 1989 Loma Prieta earthquake (Figure 2) and in Olympia, WA, during the February 2001 Nisqually earthquake. Yet another example can be seen on the Moon in the terraced walls of the Copernicus crater. After the impact that formed the crater, gases trapped in the soil caused the lunar soil to lose strength and slide.

Liquefaction Phenomena

Sandy soils are usually good foundation soils as long as they are not subjected to dynamic (shaking) load conditions. The packing density and degree of saturation (dry versus fully saturated case, where pore spaces are filled with water) are the main factors that will determine how the sand deposit will react to a dynamic or cyclic load effect (e.g., earthquake load). When sandy soil deposits lie under the ground water table level in an earthquake-prone zone (e.g., the U.S. West Coast and Japan), then there is a high risk of sand **liquefaction** if the area becomes the scene of a strong earthquake. Liquefaction can be simply illustrated by the schematic shown in Figure 1, where loose packing of sand grains (i.e., large void volumes between sand grains) exists under the water table (also called fully saturated sand layer). Cyclic loads, such as loads that develop as a result of an earthquake, cause sand particles to lose contact with each other as a result of a sudden increase in the pore water pressure (i.e., sand grains will float in water). Therefore, the soil will have zero strength since there is no contact between particles. We say the soil liquefied. After the excess pore water pressure dissipates, the sand particles settle in a denser condition, which results in excessive settlement for buildings and structures.

Studying Soil Mechanics in Space

Detailed understanding of this phenomenon is needed to improve techniques for evaluating building sites here on Earth and, eventually, on the Moon and Mars, and to improve industrial processes that handle powdered materials. Research can only go so far on Earth because gravity-induced stresses complicate the analysis and change loads too quickly for detailed study. Going to orbit, though, opens new possibilities.

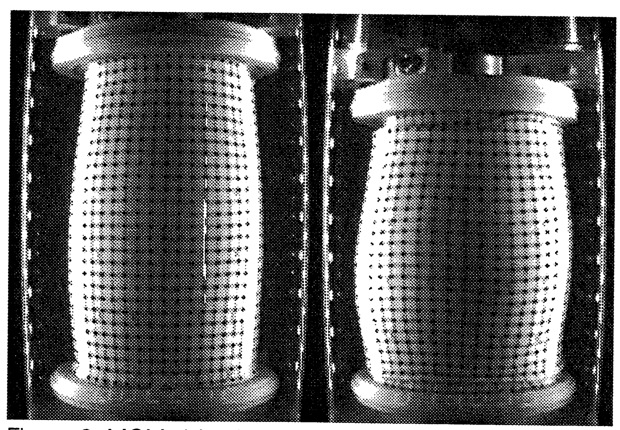


Figure 3. MGM video images show a sand column shortly after the start of an onorbit experiment (left) and an hour later, near completion (right). (NASA)

The Mechanics of Granular Materials (MGM; Figure 3) experiment uses the **microgravity** of orbit to test sand columns under conditions that cannot be obtained in experiments on Earth. This new knowledge will be applied to improving foundations for

buildings, managing undeveloped land, and handling powdered and granular materials in chemical, agricultural, and other industries.

The weightless environment of space allows soil mechanics experiments at **low effective stresses** with very **low confining pressures** to proceed slowly for detailed study. Specimen weight is no longer a factor, and the stress across the specimen is constant. This yields measurements that can be applied to larger problems on Earth.

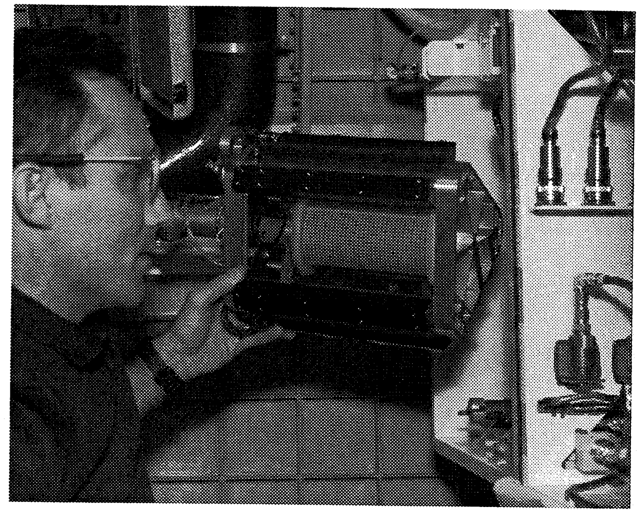


Figure 4. An astronaut inserts a soil sample module into the MGM apparatus in the Space Shuttle middeck. (NASA)

MGM has flown twice on the Space Shuttle (STS-79 and -89; Figure 4), involving nine dry sand specimens. These were highly successful, showing strength properties two to three times greater and stiffness properties ten times greater than conventional theory predicted. On the STS-107 mission (scheduled for 2002), MGM scientists will investigate conditions with water-saturated sand resembling soil on Earth. Three sand specimens will be used in nine experiments. MGM can also benefit from extended tests aboard the International Space Station, including experiments under simulated lunar and Martian gravity in the science centrifuge.

The heart of MGM is a column of 1.3 kg (2.8 lbs) of sand, 7.5 cm in diameter by 15 cm tall (3 x 6 in). This is Ottawa F-75 banding sand, a natural quartz sand (silicon dioxide) with fine grains 0.1 to 0.3 mm in diameter. Ottawa sand is widely used in civil engineering experiments and evaluations. The sand is contained in a latex sleeve printed with a grid pattern so cameras can record changes in shape and position. Tungsten metal plates on three guide rods cap each end of the specimen. The specimen assembly is contained in a test cell shaped like an equilateral prism and comprising a Lexan jacket filled with pressurized water to confine and stabilize the specimen during launch and re-entry. An electric stepper motor moves the top platen to compress and relax the sand column. A load cell measures forces. The test cell is held on a rigid test/observation pad mounted between an array of three CCD cameras. Because this mechanism is too complex to replicate in a classroom, this exercise uses a simpler device.

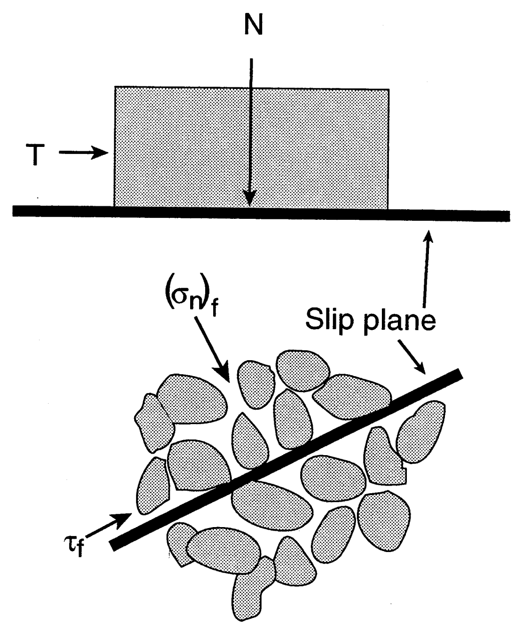


Figure 5. (a) Slip of a wooden block, (b) A slip plane in a soil mass (*Budhu, 2000*).

Coulomb's Friction Law

You may recall Coulomb's friction law from your physics courses. If a wooden block is pushed horizontally across a table (Figure 5), the horizontal force (T) required to initiate the movement is given in Equation (1) where μ is the **coefficient of static friction** between the block and the table and N is the **normal force**. The **friction angle** ϕ is related to μ ($\tan \phi = \mu$). In terms of stress, Coulomb's law for sand is expressed

as Equation (2) where τ_f is the **shear stress** when the slip plane is initiated ($\tau_f = T/A$, where T is the **shear force** at impending slip and A is the area of plane parallel to T), and σ_n is the **normal stress** on the plane on which slip is initiated ($\sigma_n = N/A$, where N is the resultant normal force acting on the slip plane). Failure does not necessarily mean collapse but the initiation of movement of one rigid body relative to another.

Friction equations	
$T = \mu N$	(1)
$\tau_f = \sigma_n \tan \phi$	(2)

Direct Shear Test

Civil engineers use standard procedures such as the conventional triaxial test, Direct Shear Test (DST), and simple shear test to measure the shear strength of soils. Such procedures require special apparatuses that meet certain standards. This educational brief illustrates the standard direct shear test to determine the shear strength of soils. The standard procedure is modified to enable students (grades 9–12) to perform experiments using materials available at local hardware stores.

> ***Note:*** *This experiment should only be used for educational demonstrations because it uses non-standard equipment. The results will not be valid in a real-world civil engineering application.*

The DST apparatus consists of a horizontally split box (Figure 6) and a frame to apply a horizontal shear load (T) under constant normal load (N). It is known as a shear box. Soil is placed in the shear box, where the top half is moved relative to the horizontal plane (AB). Normal (or vertical) force (N) is applied through a platen or plate resting on the top of the soil. The shear force (T) is applied through a motor for displacement control or by weights through a pulley system for load control. Usually, three or more tests are carried out on a soil sample using three different constant vertical forces. Failure is determined when the soil cannot resist any further increment of horizontal force (i.e., when the upper box slips). If you plot shear stress versus normal stress, you get a straight line with a slope equal to ϕ (Figure 7).

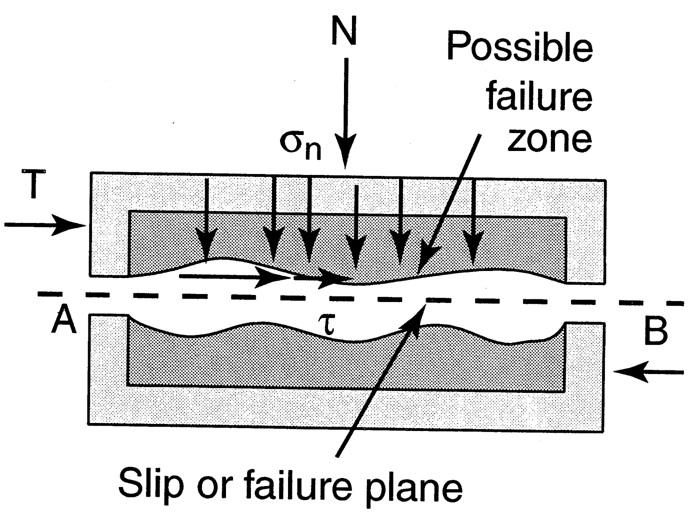


Figure 6. Shear box (*Budhu, 2000*).

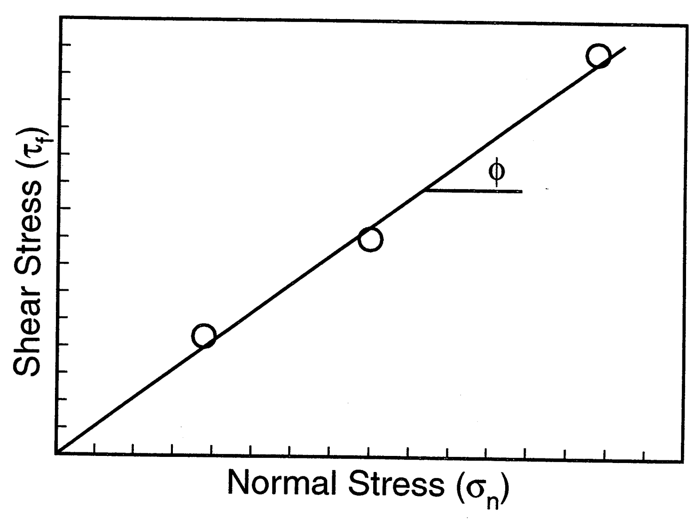


Figure 7. Coulomb shear stress versus normal stress relation.

DST Apparatus

Follow these steps to build the DST apparatus (Figures 8–10; see the materials list on page 8):

- Wear workshop goggles to protect your eyes. Use all tools responsibly.
- Use wood available at local hardware stores to build the bottom half of the shear box with one side closed having internal dimensions of 80 x 80 x 40 mm with wall thickness of 12.7 mm (1/2 in). Wall thickness may vary from 3/8 to 1.0 inch depending on what is available in the store. Do not use plywood; it will fragment when nails or screws are inserted through the edges.
- Build the top half of the box with internal dimensions of 80 x 80 x 60 mm with the same wall thickness as step one.
- Put the two parts of the box together. Drill two centered 3.18 mm (1/8 in) diameter holes through the walls of the top half of the box. Next, drill holes 12.7 mm (1/2 in) deep in the bottom-half wall.
- Place very thin spacers, such as toothpicks, on the four sides of the shear box (with thickness larger than the diameter of the largest sand particle or approximately 0.5 mm thick). Put the top half of the shear box on the bottom half and attach it using pins, screws, or nails.
- Cut the shear box cap. It is a piece of wood that measures 79 x 79 x 50 mm. It should fit inside the shear box as shown in Figure 9.

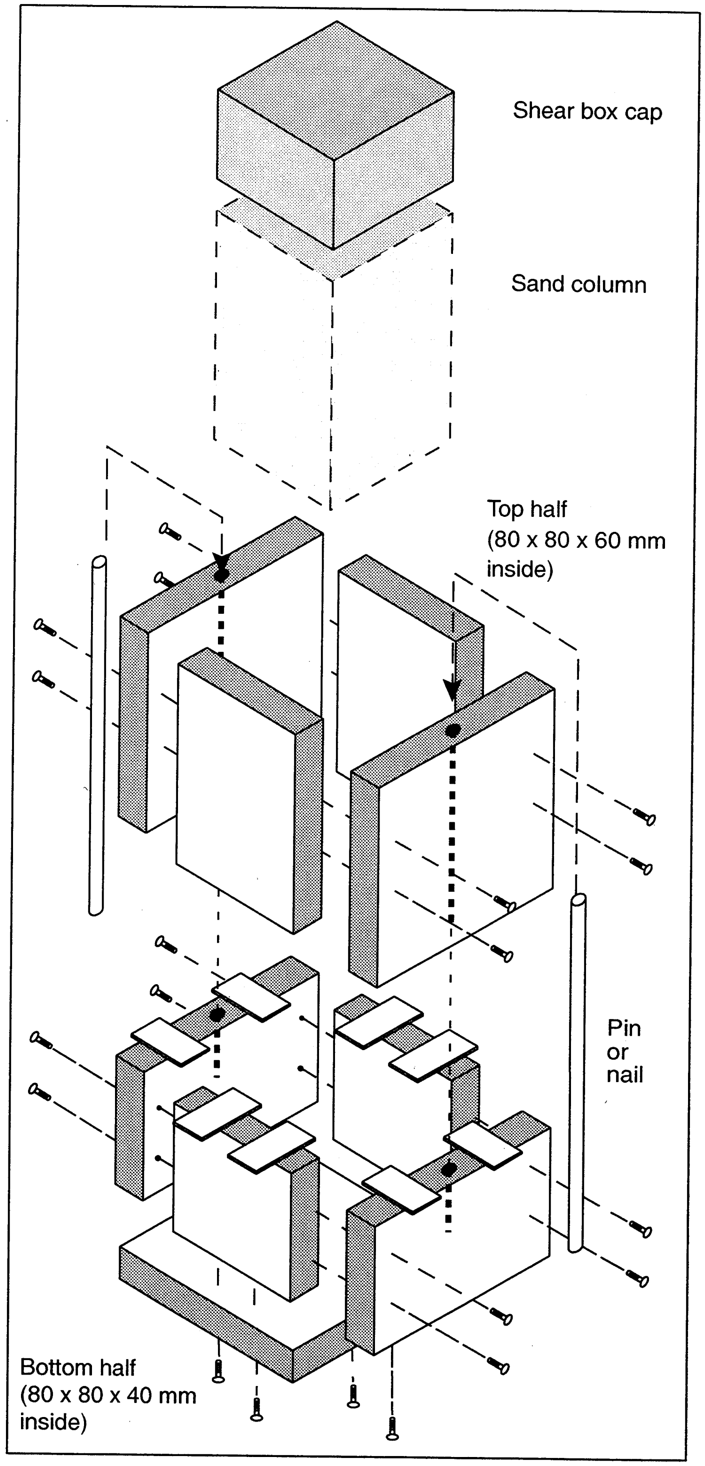


Figure 8. Exploded view of Direct Shear Test box; light gray volume indicates sand.

- Attach the bottom half of the shear box to a table or a laboratory bench using a piece of wood or another method (i.e., angles, screws, C-clamp, etc.).
- Attach an eye hook to the center of one face in the top half of the box.

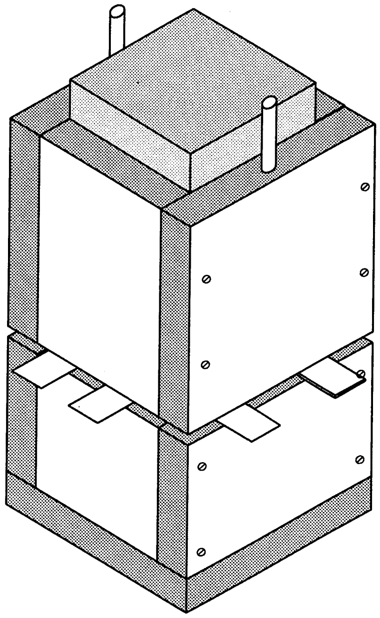


Figure 9. Assembled DST box with shims in place.

- Attach the string, pulley and weight platform to the eye hook on the top half of the shear box.

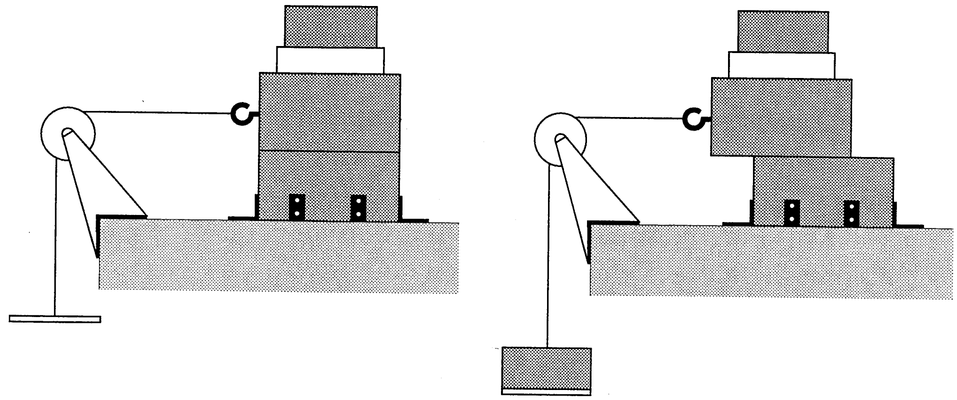


Figure 10. DST box at start of test (left) and weight is added to cause displacement (right).

Materials list and estimates prices for shear strength of sand experiment

	quantity*	price /unit	total price**
Medium density fiberboard (0.5 in x 2 x 2 ft)***	1	4.00	4.00
(3) 12.7 x 105.4 x 105.4 mm (0.5 x 4.15 x 4.15 in)			
(2) 12.7 x 105.4 x 40 mm (0.5 x 4.15 x 1.57 in)			
(2) 12.7 x 80 x 40 mm (0.5 x 3.14 x 1.57 in)			
(2) 12.7 x 105.4 x 60 mm (0.5 x 4.15 x 2.36 in)			
(2) 12.7 x 80 x 60 mm (0.5 x 3.14 x 1.57 in)			
Box of metal pins ~3 x 85 mm (1/8 x 3.3 in; only 2 needed)	1	1.88	1.88
Pack of .5 mm shims	1	4.00	4.00
Wood block 79 x 79 x 50 mm	1	0.31	0.31
Pack (100) 1-inch Phillips screws	1	3.89	5.00
Pack of eye hooks	1	0.83	0.83
Pulley	1	3.50	3.50
Small bucket (weight platform)	1	2.00	2.00
Angles	8	0.53	4.24
5 lb bag of sand	1	2.54	2.54
Screwdriver	1	3.97	3.97
Roll of string	1	2.00	2.00
Wood glue	1	3.00	3.00
Grand total			37.27

* Some items must be purchased in a bag even though only one or two are needed for this project. You may vary sizes if they perform the same function. ** Example prices only. Actual prices may vary with location. *** Some stores will cut to requested size. Because this is a classroom demonstration, variations from exact dimensions are okay. What is more important is following the procedure.

Experiment Procedure

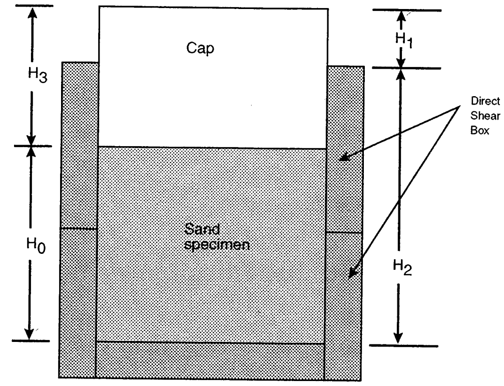


Figure 11. Determining the height of the sand specimen.

Record all data on the data sheet at the end of this brief.

- Obtain a sample of about 3,000 g (~6.5 lb) of dry, clean sand. You can purchase it from local hardware stores or from swimming pool supply stores (uniform sand is used as a filter material in many applications).
- Weigh the cap and record its mass (M_{cap}).
- Assemble the direct shear box, and mount it on the laboratory bench (Figure 10).
- Measure the depth, H_2, of the shear box and the height, H_3, of the top cap as shown in Figure 11. Record these measurements.
- Weigh the dish filled with the sand to be tested. Place the sand in a container (e.g., beaker or dish) then weigh the dish with the sand and record the weight.
- Pour the sand slowly into the shear box while the pins hold the two parts of the shear box together. Compact the sand with a rubber tamper or gently vibrate the table with your fist. The shear box should be filled with enough material so that the depth of sand in the shear box is above the slip or failure plane (i.e., about 80 mm deep).
- Weigh the container with the leftover sand not poured into the box to determine the weight of the sand used in the test.
- Level the sand surface inside the shear box, put on the cap.
- Put a mass (M_N, approximately 500 g or any mass you choose) on the top of the cap.
- Measure the initial height, H_0, of the sand specimen by measuring the distance, H_1, as shown in Figure 11. Record this measurement.
- Carefully remove the shims and the pins.
- Weigh the weight platform (this can be a small bucket) and record the weight. Attach it to the shear box using a string (Figure 12).

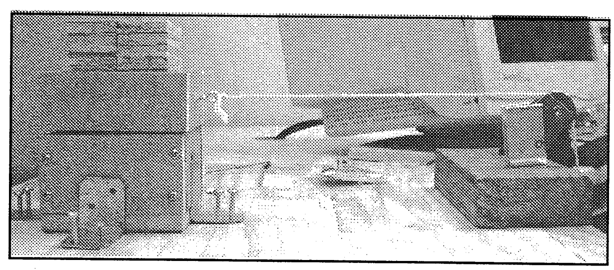


Figure 12. An assembled DST box, ready to slide.

- Gently add weight in 50-gram increments to the weight platform (add sand to the bucket to apply the weight increments) and watch if the top half of the shear box moves or not. Keep adding weights until the top half of the shear box starts sliding along the shear plane (Figure 10).
- Record the mass (M_S) that caused the shearing.

- Take the shear box apart and clean the sand.
- Repeat the test (steps 3 through 14) for at least two other M_N values using sand samples that have a weight close to that of the first sample.

Calculations

- Calculate the initial volume of the sand specimen (V_0) as: $V_0 = 0.08 \times 0.08 \times H_0$.
- Calculate the specimen cross-sectional area, A, as: $A = 0.08 \times 0.08 = 0.0064\ m^2$.
- Calculate the sand dry unit weight (γd) as: γd = [(mass of sand in kg) x g]/V_0; $g = 9.81\ m/sec^2$.
- Calculate the normal force (N) as: $N = (M_N + M_{cap}) \times g$.
- Calculate the shear force (T) as: $T = (M_N + \text{platform mass}) \times g$.
- Calculate the normal stress (σ_n) as: $\sigma_n = N/A$.
- Calculate the shear stress at failure (τ_f) as: $\tau_f = T/A$.
- Repeat for all N values (you need at least three experiments with similar sand unit weights).
- Plot σ_n -τ_f relation as shown in Figure 3 and fit a straight line through the data points. Calculate the value of the sand friction angle (ϕ) in degrees?

Extensions

Repeat the experiments with sand under different conditions and compare with the original tests:

1. Sand that has been **tamped** down by gently hammering on the cap.
2. Sand that has been settled by vibrating for several minutes (for example, by pressing the side of a power tool against the box with the tool on; leave the cap atop the sand).
3. Sand that has water added. Do this in discrete increments (i.e., add water equal to 5 percent of the mass of the sand, then 10 percent).
4. Tamp the wet sand to squeeze out as much water as possible and repeat.

LABORATORY DIRECT SHEAR TEST DATA SHEET

Date: ______________________________

Tested by: ___________________________

Description of the sample: ______________________________

[A] Specimen Data: Specimen no.			
1. Mass of the cap (M_{cap}), g			
2. Mass of the dish with sand, g			
3. Mass of the dish and leftover sand, g			
4. Mass of the sand specimen [i.e., (2) – (3)], g			
5. Mass of the weight platform, g			
6. Measure H_2, mm			
7. Measure H_3, mm			
8. Measure H_1, mm			
9. Calculate H_0 [$H_0 = H_1 + H_2 - H_3$], mm			
10. Calculate the specimen area, *A*, Mcap			
11. Calculate the initial volume, V_0, m^3			
12. Calculate specimen dry unit weight, gd, kN/m^3			
[B] Stress Data			
1. Normal mass (M_N), g			
2. Calculate normal force (*N*), kN			
3. Calculate normal stress (σ_n), kN/m^2			
4. Shear mass (M_S), g			
5. Calculate shear force (*T*), kN			
6. Calculate shear stress (τ_f), kN/m^2			

Glossary

coefficient of static friction — a dimensionless constant representing the static (stationary) friction between two objects; the value of this coefficient depends on the objects involved and on the condition of their surfaces

cohesion — the intermolecular force that holds together the molecules in a solid or liquid

confining pressure — initial normal stress

effective stress — the average stress carried by the soil particles

electromagnetic force — an attraction or repulsion between two charged particles that are in relative motion; one of the fundamental forces of interaction which influences charged entities

electrostatic force — an attraction or repulsion between two charged particles that are not in motion

external loading — an external force applied to an existing object

friction — the resistance to relative motion between two surfaces in contact

friction angle — an index value to measure the friction property of soils

geometric interlocking — the connection of two or more particles based on their shape

interparticle friction — the friction between two adjacent particles

liquefaction — the conversion of a solid or a gas into a liquid

load — anything that must be supported or moved

microgravity — an environment in which the apparent weight of a system is small compared its actual weight due to gravity

normal force — the component of support force perpendicular to a supporting surface; this force acts at right angles to the surface

normal stress — the load per unit area on a plane normal to (at right angles to) the direction of the load

packing density — the mass of particles that can be placed within a specific volume

shear force — a tangential force acting on one face of an object while the opposite face is held fixed

shear strength — the maximum internal frictional resistance of a soil to applied shearing forces

shear stress — the load per unit area on a plane parallel to the direction of the shear force

shearing — a type of deformation that occurs when a body is subjected to a force tangential to one of its faces while the opposite face is held in a fixed position by a force of friction

tamp — to pack down tightly by a succession of blows or taps

References

Youd, T. L. (1977), "Packing Changes and Liquefaction Susceptibility," *ASCE Journal of Geotechnical Engineering*, 103:918-922. (Figure 1)

Budhu, M. (2000). Soil Mechanics and Foundations. John Wiley & Sons, Inc. (Coulomb's friction law)

ASTM-D3080-98. *Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions.* (Direct shear test)

Web Links

Mechanics of Granular Materials experiment home page at NASA, *http://mgm.msfc.nasa.gov/*

Mechanics of Granular Materials experiment home page at the University of Colorado at Boulder, *http://bechtel.colorado.edu/~batiste/*

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NASA education Web site: *http://education.nasa.gov/*

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